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SUPERSYMMETRIC DARK MATTER
MSSM and SUGRA schemes in the light of a possible annual modulation effect in WIMP direct search [a]

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Abstract

Recently the DAMA/NaI Collaboration reported further indication of a possible modulation effect in WIMP direct detection. In this note we discuss the relevance of this result for supersymmetric theories where the neutralino is the dark matter candidate. We specifically consider the Minimal Supersymmetric extension of the Standard Model (MSSM) and Supergravity-inspired schemes, with possible deviations of the unification conditions at the GUT scale in the Higgs sector. The main results of our analysis show that the annual modulation data are widely compatible with an interpretation in terms of a relic neutralino as the major component of dark matter in the Universe. We also discuss the implications for searches of supersymmetry at accelerators and for indirect searches of neutralino dark matter.

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[a] Report on the work done in collaboration with A. Bottino, F. Donato and S. Scopel.

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Recently the DAMA/NaI Collaboration reported further indication of a possible modulation effect in WIMP direct detection. In this note we discuss the relevance of this result for supersymmetric theories where the neutralino is the dark matter candidate. We specifically consider the Minimal Supersymmetric extension of the Standard Model (MSSM) and Supergravity-inspired schemes, with possible deviations of the unification conditions at the GUT scale in the Higgs sector. The main results of our analysis show that the annual modulation data are widely compatible with an interpretation in terms of a relic neutralino as the major component of dark matter in the Universe. We also discuss the implications for searches of supersymmetry at accelerators and for indirect searches of neutralino dark matter.

1 Introduction

The presence of non–baryonic dark matter in our Galaxy can be probed by means of different techniques which attempt to detect either directly (through elastic scattering off nuclei) or indirectly (through products of annihilation) the dark matter particles which are supposed to be embedded in the galactic halo. It has been shown (see, e.g., Ref. [1]) that the sensitivities of the present experiments is currently at the level required for the study of one of the most appealing particle candidates for dark matter, the neutralino. This implies that it is now feasible to start the investigation of possible signatures in the detection rates, originated by specific features related to the presence of the dark matter particles.

In the case of direct detection, a typical signature consists in the annual modulation of the detection rate. This effect was first pointed out in the seminal papers of Refs. [2], where it was observed that, during the orbital motion of the Earth around the Sun, the change of direction of the relic particle velocities with respect to the detector induces a time dependence in the differential detection rate, i.e. $S(E,t) = S_0(E) + S_m(E)\cos[\omega(t-t_0)]$, where $\omega = 2\pi/365$ days and $t_0 = 153$ days (June $2^{\rm nd}$). $S_0(E)$ is the average (unmodulated) differential rate and $S_m(E)$ is the modulation amplitude of the rate. The relative importance of $S_m(E)$ with respect to $S_0(E)$ for a given detector, depends both on the mass of the dark matter particle and on the value of the recoil energy

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where the effect is looked at. Typical values of $S_m(E)/S_0(E)$ for a NaI detector range from a few percent up to $\sim$ 15%, for WIMP masses of the order of 20–80 GeV and recoil energies below 8–10 KeV.

Over the last year, the DAMA/NaI Collaboration reported on two different analyses of the data collected during two periods of data taking, obtained with an experimental set–up consisting of nine 9.70 Kg NaI(Tl) detectors [3,4]. The data have been analysed by employing a maximum likelihood method, which allows to test the hypothesis of the presence of a yearly modulated signal against a time–independent background, by properly considering the energy and time behaviour expected for a recoil of massive WIMPs. The remarkable result of Refs. [3,4] is that the data support the possible presence of an annual modulation effect induced by WIMPS in the counting rate of the detector. By combining the data of the two periods of data taking, a total exposure of 19,511 kg $\times$ day has been collected. The maximum likelihood analysis indicates that the hypothesis of presence of modulation against the hypothesis of absence of modulation is statistically favoured at 99.6% C.L., and pins down a 2–σ C.L. region in the plane $\xi\sigma_{\rm scalar}^{\rm (nucleon)} - m_\chi$, where m_χ is the WIMP mass, $\sigma_{\rm scalar}^{\rm (nucleon)}$ is the WIMP–nucleon scalar elastic cross section and $\xi = \rho_\chi/\rho_l$ is the fractional amount of local WIMP density ρ_χ with respect to the total local dark matter density ρ_l. This region is plotted in Fig.1 as a closed dashed curve, for $\rho_l = 0.3$ GeV cm^{-3}. The ensuing 1–σ ranges for the two quantities are: $m_\chi = 59^{+22}_{-14}$ GeV and $\xi\sigma_{\rm scalar}^{\rm (nucleon)} = 7.0^{+0.4}_{-1.7}\times10^{-9}$ nb [4]. These results refer to $v_{\rm rms} = 270$ Km s^{-1} for the velocity dispersion of the WIMP Maxwellian velocity distribution in the halo, $v_{\rm esc} = 650$ Km s^{-1} for the WIMP escape velocity and $v_\odot = 232$ Km s^{-1} for the velocity of the Sun around the galactic centre. We notice that a variation of these velocity parameters inside their 2–σ ranges of uncertainty affects the maximum likelihood value of m_χ and $\xi\sigma_{\rm scalar}^{\rm (nucleon)}$ by roughly $\pm$ 30% and by $\sim \pm$ 12%, respectively.

In this paper, which is based on the results obtained in Refs. [5,6,7] we derive the theoretical implications of the experimental data of Refs. [3,4], assuming that the indication of the possible annual modulation is due to relic neutralinos and we show that these data are fully compatible with an interpretation in terms of a relic neutralino as the major component of dark matter in the Universe. We select the relevant susy configurations in two different frameworks: the low energy minimal supersymmetric extension of the standard model (MSSM) and supergravity–inspired schemes (SUGRA models). In the latter case, we will explicitly consider both a strict unification at the GUT scale and the possibility of deviation from universality in the Higgs sector. The present analysis extends a previous analysis of ours [8] referring to the experimental data of Ref. [3]. We then finally also discuss how the susy configurations, selected by the annual

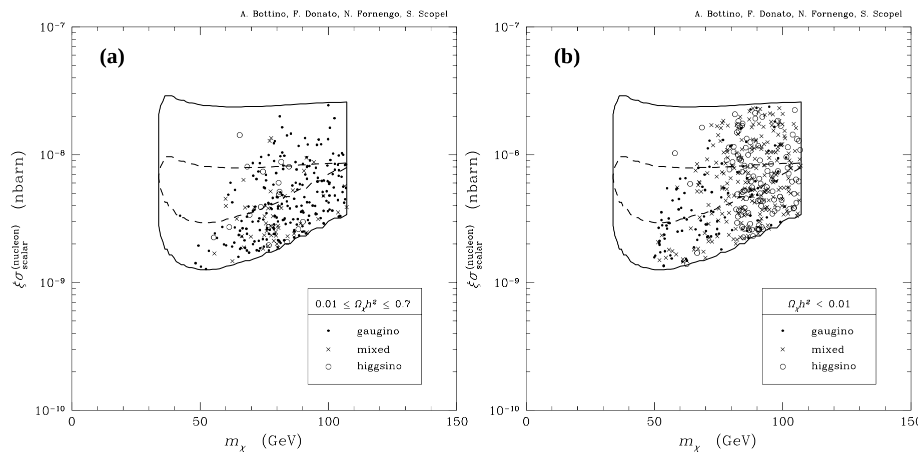

Figure 1: Scatter plot of **MSSM** configurations compatible with the annual modulation data in the plane m_χ–$\xi\sigma_{\rm scalar}^{\rm (nucleon)}$. The dashed contour line delimits the 2–σ C.L. region, obtained by the DAMA/NaI Collaboration, by combining together the data of the two running periods of the annual modulation experiment. The solid contour line is obtained from the dashed line, which refers to $\rho_l = 0.3$ GeV cm^{-3}, by accounting for the uncertainty range of ρ_l. (a) and (b) refer to configurations with $0.01 \le \Omega_\chi h^2 \le 0.7$ and with $\Omega_\chi h^2 < 0.01$, respectively.

modulation data, can be investigated by indirect searches for relic WIMPs and at accelerators.

2 Selection of susy configurations by the annual modulation data

In order to discuss which region in the susy parameter space is selected by the DAMA data, we first convert the region delimited by the 2–σ C.L. dashed contour line of Fig.1 into an enlarged one, which accounts for the uncertainty in the value of ρ_l, due to a possible flattening of the dark matter halo and a possibly sizeable baryonic contribution to the galactic dark matter: 0.1 GeV cm$^{-3} \le \rho_l \le 0.7$ GeV cm^{-3}. One then obtains the 2–σ C.L. region denoted by a solid contour in Fig.1 (hereafter denoted as region R). The susy configurations are then selected by the requirement that $(m_\chi, \xi\sigma_{\rm scalar}^{\rm (nucleon)}) \in R$, when m_χ, $\sigma_{\rm scalar}^{\rm (nucleon)}$ and ξ are evaluated in the MSSM and SUGRA schemes. As for the values to be assigned to the quantity $\xi = \rho_\chi/\rho_l$ we adopt the standard rescaling recipe [5]: $\xi = \min[1, \Omega_\chi h^2/(\Omega h^2)_{\rm min}]$, where $\Omega_\chi h^2$ denotes the neutralino relic abundance, calculated in the susy model [9], and $(\Omega h^2)_{\rm min}$ is a minimal value compatible with observational data and with large–scale structure calculations. We use here the value $(\Omega h^2)_{\rm min} = 0.01$ [5]. In all our analyses, we consider as cosmologically acceptable all configurations which provide $\Omega_\chi h^2 \le 0.7$.

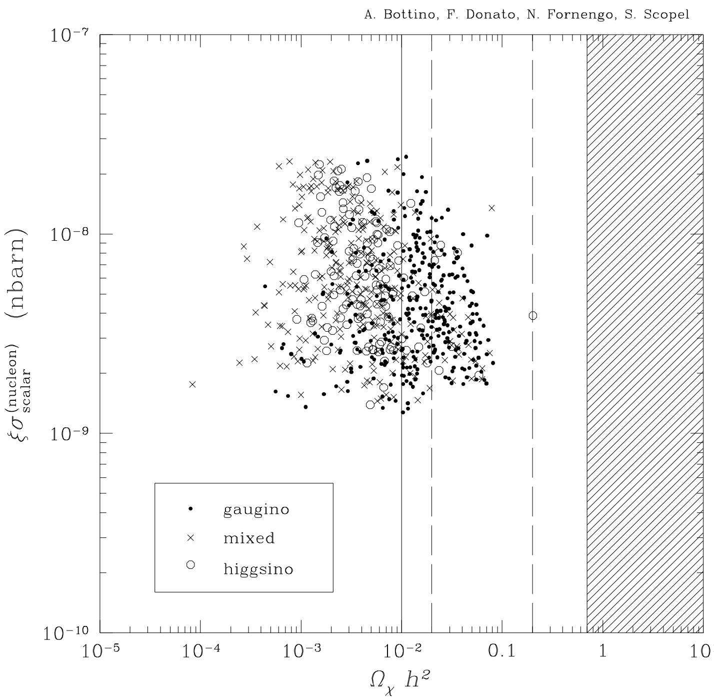

Figure 2: Scatter plot of **MSSM** configurations compatible with the annual modulation data in the plane $\Omega_\chi h^2 - \xi\sigma_{\rm scalar}^{\rm (nucleon)}$. The two vertical solid lines delimit the $\Omega_\chi h^2$–range of cosmological interest. The two dashed lines delimit the most appealing interval for $\Omega_\chi h^2$, as suggested by the most recent observational data. The hatched area is excluded by cosmology.

3 Analysis in the MSSM

In our first analysis [5] we employ the minimal supersymmetric extension of the standard model (MSSM) which conveniently describes the susy phenomenology at the electroweak scale, without too strong theoretical assumptions. The MSSM is based on the same gauge group as the Standard Model, contains the susy extension of its particle content and two Higgs doublets. The free parameters of the model are: the SU(2) gaugino mass parameter M_2, related to the U(1) gaugino mass parameter by the GUT relation $M_1 = (5/3)\tan^2\theta_W M_2$; the Higgs–mixing parameter μ; the ratio of the two Higgs vev's $\tan\beta$; the mass of the pseudoscalar neutral Higgs m_A; a common soft–mass parameter for all the squarks and sfermions m_0; a common trilinear parameter for the third family A (the other trilinear parameters are all set to zero). The parameters are varied in the following ranges: 10 GeV $\leq M_2 \leq$ 500 GeV, 10 GeV $\leq |\mu| \leq$ 500 GeV, 75 GeV $\leq m_A \leq$ 1 TeV, 100 GeV $\leq m_0 \leq$ 1 TeV, $-3 \leq A \leq$

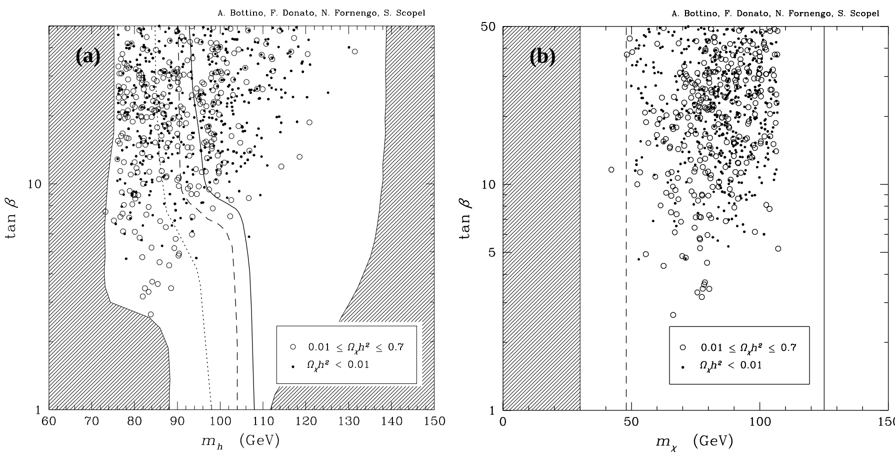

Figure 3: Explorability at accelerators of the **MSSM** configurations compatible with the annual modulation data. (a): Scatter plot in the plane m_h – $\tan\beta$. The hatched region on the right is excluded by theory. The hatched region on the left is excluded by present LEP data at 183 GeV. The dotted and the dashed curves denote the reach of LEP2 at energies 192 GeV and 200 GeV, respectively. The solid line represents the 95% C.L. bound reachable at LEP2, in case of non discovery of a neutral Higgs boson. (b): Scatter plot in the plane m_χ – $\tan\beta$. The hatched region on the left is excluded by present LEP data. The dashed and the solid vertical lines denote the reach of LEP2 and TeV33, respectively.

$+3$, $1 \le \tan\beta \le 50$.

Our susy parameter space is constrained by the latest data from LEP2 on Higgs, neutralino, chargino and sfermion masses [11]. Moreover, the constraints due to the $b \to s + \gamma$ process has been taken into account, considering the latest results both in the theoretical evaluation and in the experimental determination of the branching ratio [12].

By varying the susy parameters inside the ranges defined above, we find that a large portion of the modulation region R is indeed covered by susy configurations, compatible with all present physical constraints. This set of susy states (set S) is displayed in Fig.1 with different symbols, depending on the neutralino composition. In Fig.1(a) we notice that a quite sizeable portion of region R is populated by susy configurations with neutralino relic abundance inside the cosmologically interesting range $0.01 \lesssim \Omega_\chi h^2 \lesssim 0.7$. Thus we obtain the first main result of our analysis, i.e. *the annual modulation region, singled out by the DAMA/NaI experiment, is largely compatible with a relic neutralino as the major component of dark matter*. This is certainly the most remarkable possibility. However, we also keep under consideration neutralino configurations with a small contribution to $\Omega_\chi h^2$ (see Fig.1(b)), since also the detection of relic particles with these features would provide in itself a very noticeable information.

The neutralino relic abundance $\Omega_\chi h^2$ is plotted versus $\xi\sigma^{(\rm nucleon)}_{\rm scalar}$ in Fig.2. We notice that a large fraction of the neutralino relic abundance falls into the restricted range $0.02 \lesssim \Omega_{\rm CDM}h^2 \lesssim 0.2$, which turns out to be the most appealing interval for relic neutralinos as indicated from recent observations and analyses on the value of the matter content of the Universe [5].

The properties of set S relevant to searches at accelerators are displayed in Fig.3. Section (a) of this figure shows a scatter plot of set S in term of m_h and $\tan\beta$, where it is apparent a correlation between $\tan\beta$ and m_h. This is due to the fact that the rather large values $\sigma^{(\rm nucleon)}_{\rm scalar} \sim (10^{-9} - 10^{-8})$ nb, as required by the annual modulation data, impose that either the couplings are large (then large $\tan\beta$) and/or the process goes through the exchange of a light particle. Thus, Higgs–exchange dominance (which turns out to occur here) and $\sigma^{(\rm nucleon)}_{\rm scalar} \sim (10^{-9} - 10^{-8})$ nb require a very light h at small $\tan\beta$, and even put *a lower bound on tan β:* $\tan\beta \gtrsim 2.5$. From Fig.3(a) we notice that a good deal of susy configurations are explorable at LEP2, while others will require experimental investigation at a high luminosity Fermilab Tevatron, which should be capable to explore Higgs masses up to $m_h \sim 130$ GeV. In Fig.3(b) we display the scatter plot of set S in the plane $m_\chi - \tan\beta$. Since the reach of LEP2 extends only up to the dashed vertical line, at $m_\chi \simeq 50$ GeV, the exploration of the whole interesting region will require Tevatron upgrades or LHC. Under favorable hypothesis, TeV33 could provide exploration up to the vertical solid line.

4 Analysis in SUGRA schemes

In this Section we show that the susy features, implied by the DAMA/NaI data, are also compatible with more ambitious supersymmetry schemes, where the previous phenomenological model is implemented in a supergravity (SUGRA) framework, especially if the unification conditions, which are frequently imposed at the Grand Unification (GUT) scale, are appropriately relaxed [6].

The essential elements of the SUGRA models employed here are: a Yang–Mills Lagrangian, the superpotential and the soft–breaking Lagrangian. In this class of models the electroweak symmetry breaking (EWSB) is induced radiatively. This supergravity framework is usually implemented by some restrictive assumptions about unification at M_{GUT}: (i) unification of the gaugino masses: $M_i(M_{GUT}) \equiv m_{1/2}$, (ii) universality of the scalar masses: $m_i(M_{GUT}) \equiv m_0$, (iii) universality of the trilinear scalar couplings: $A^l(M_{GUT}) = A^d(M_{GUT}) = A^u(M_{GUT}) \equiv A_0 m_0$. As extensively discussed in Ref. [10], these conditions have strong consequences for low–energy supersymmetry phenomenology, and in particular for the properties of the neutralino.

The unification conditions represent a theoretically attractive possibility,

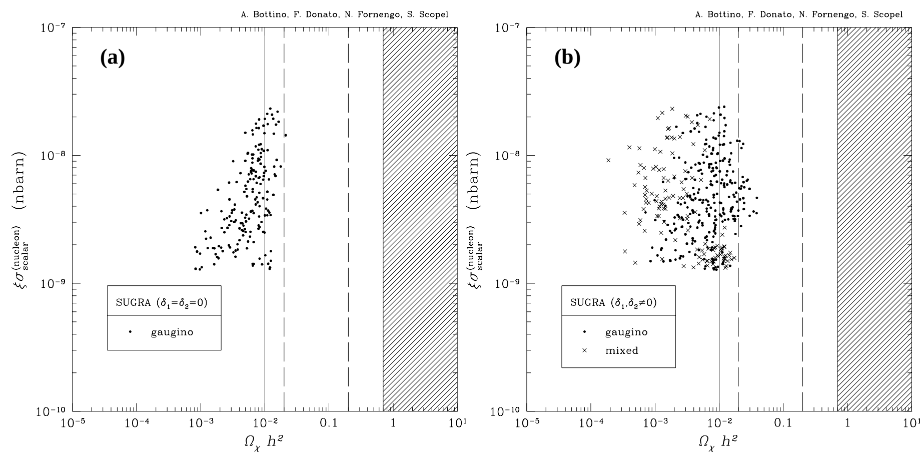

Figure 4: Scatter plot of **SUGRA** configurations compatible with the annual modulation data in the plane $\Omega_\chi h^2$ – $\xi\sigma^{(\rm nucleon)}_{\rm scalar}$. (a): universal SUGRA models. (b): SUGRA models with deviations from universality in the Higgs sector. Notations are as in Fig.2.

which makes strictly universal SUGRA models very predictive. However, the above assumptions, particularly (ii) and (iii), are not fully justified, since universality may occur at a scale higher than M_{GUT}, i.e. the Planck scale or string scale, in which case renormalization above M_{GUT} weakens universality. We therefore discuss the DAMA/NaI data both in a SUGRA model with strict unification conditions and in a SUGRA framework, where we introduce a departure from universality in the scalar masses at M_{GUT} which splits the Higgs mass parameters: $M^2_{H_i}(M_{GUT}) = m_0^2(1+\delta_i)$. The parameters δ_i will be varied in the range (-1,+1), but are taken to be independent of the other susy parameters.

Because of the requirements of radiative EWSB and of the universality conditions, the independent susy parameters are reduced to (apart from the δ_i's): $m_{1/2}, m_0, A_0, \tan\beta$ and sign(μ). They are varied in the following ranges: 10 GeV $\leq m_{1/2} \leq$ 500 GeV, $m_0 \leq$ 1 TeV, $-3 \leq A_0 \leq +3$, $1 \leq \tan\beta \leq 50$; the parameter μ is taken positive. The values taken as upper limits of the ranges for $m_{1/2}, m_0$ are inspired by the upper bounds which may be derived for these quantities in SUGRA theories, when one requires that the EWSB, radiatively induced by the soft supersymmetry breaking, does not occur with excessive fine tuning. The same argument was also used in the previous Section in setting the upper limits on the dimensional parameters of the MSSM.

The susy parameter space is constrained by the same experimental bounds discussed in the previous Section for the MSSM, with the additional constraint

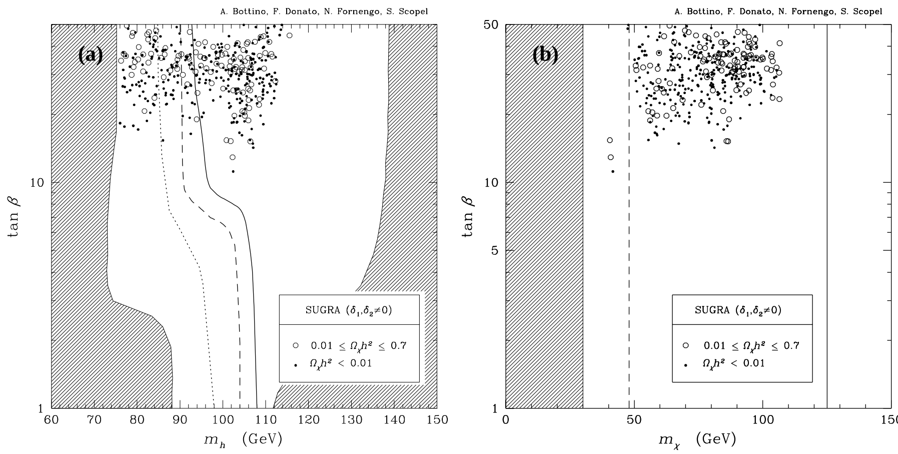

Figure 5: Explorability at accelerators of the **non–universal SUGRA** configurations compatible with the annual modulation data. (a): Scatter plot in the plane $m_h - \tan\beta$. (b): Scatter plot in the plane $m_\chi - \tan\beta$. Notations are as in Fig.3.

arising from the limits on the bottom–quark mass m_b. The bottom mass is computed as a function of the susy parameters and required to be compatible with the present experimental bounds [13].

The susy configurations compatible with the DAMA data are shown in the plane $\xi\sigma^{(\rm nucleon)}_{\rm scalar} - \Omega_\chi h^2$ in Fig.4(a) for universal SUGRA models and in Fig.4(b) for models with deviation from strict universality. We notice that also in SUGRA theories a fraction of the selected susy configurations fall into the cosmologically interesting range of $\Omega_\chi h^2$.

Other qualifications for the configurations which lie inside the region R, which are relevant for searches at accelerators, concern the ranges for the h–Higgs boson mass, the neutralino mass and the lightest top–squark mass. In the case of universal SUGRA models, we find: $m_h \lesssim 115$ GeV, 50 GeV $\lesssim m_\chi \lesssim$ 100 GeV, 200 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 700 GeV and $\tan\beta \gtrsim 42$. For deviations from universality, the situation is shown in Fig.5 where we notice that the sample of representative points covers a slightly wider domain. The ranges of the Higgs and neutralino masses are similar to those already found in the universal case, but now $\tan\beta$ extends to the interval $10 \lesssim \tan\beta \lesssim 50$, instead of being limited only to very large values.

5 Indirect detection of neutralino dark matter

The susy configurations which have been proved to be compatible with the annual modulation data can also be searched for by using methods of indirect search for relic particles [7]. The two most promising techniques are the measurement of cosmic–ray antiprotons [14] and the measurement of neutrino fluxes

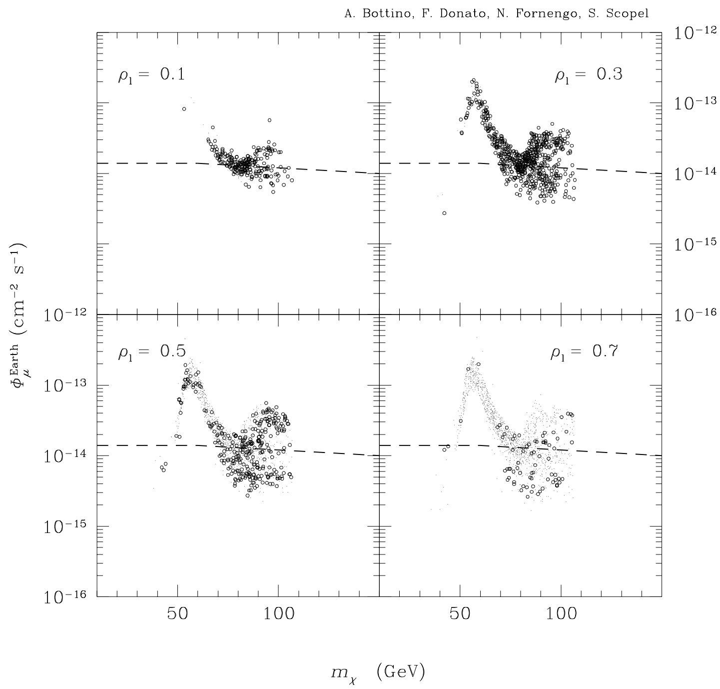

Figure 6: Scatter plots for the up–going muon fluxes from the center of the Earth versus the neutralino mass. The **MSSM** configurations compatible with the annual modulation data are subdivided into the 4 panels, depending on the corresponding value the local density: $\rho_l/(\mathrm{GeV cm}^{-3}) = 0.1, 0.3, 0.5, 0.7$. Dots denote configurations which could be excluded on the basis of the BESS95 antiproton data, circles denote configurations which survive this exclusion criterion. The dashed line denotes the MACRO upper bound.

from Earth and Sun [15].

The signals we are going to discuss here consists of the fluxes of up–going muons in a neutrino telescope, generated by neutrinos which are produced by pair annihilations of neutralinos captured and accumulated inside the Earth and the Sun. The calculation of the up–going muon signal is performed according to the method described in Ref. [15].

In Fig. 6 we display the scatter plots for the flux of the up–going muons from the center of the Earth, for various values of the local dark matter density ρ_l. In this figure is also reported the current 90% C.L. experimental upper bound on $\Phi_\mu^{\rm Earth}$, obtained by MACRO [16]. We notice the particular enhancement at $m_\chi \sim (50-60)$ GeV, due to a mass–matching effect between the WIMP and the Fe nuclei in the Earth core. It is also noticeable an effect of suppression and spreading of the fluxes for $m_\chi \gtrsim 70$ GeV at $\rho_l \gtrsim 0.3$ GeV cm^{-3}. This is due to the fact that the configurations with these large values of ρ_l may imply, because of the annual modulation data, a neutralino–nucleus cross–section which is too small to establish an efficient capture rate, necessary for the capture-annihilation equilibrium in Earth [7]. In Fig. 6 the configurations which would be excluded on the basis of the antiproton data are denoted differently from those which would survive this criterion (for details see Refs. [7,17]).

By comparing our scatter plots with the experimental MACRO upper limit, one notices that a number of susy configurations provide a flux in excess of this experimental bound and might then be considered as excluded. However, it has to be recalled that a possible neutrino oscillation effect may be operative here and affect the indirect neutralino signal as well as the background consisting in atmospheric neutrinos. Therefore a strict enforcement of the current upper bound on $\Phi_\mu^{\rm Earth}$ should be applied with caution as long as the neutrino oscillation properties are not fully considered. However, it is rewarding that the set S of susy configurations is quite accessible to relic neutralino indirect search by measurements of up–going fluxes.

6 Conclusions

In this paper, we have analysed in terms of relic neutralinos the total sample of new and former DAMA/NaI data [3,4], which provide the indication of a possible annual modulation effect in the rate for WIMP direct detection. The remarkable result of our analysis is that *the annual modulation data are widely compatible with a relic neutralino making up the major part of dark matter in the Universe*, both in the low energy MSSM and in SUGRA schemes.

We have also investigated the possibility of exploring at accelerators the same susy configurations which are compatible with the annual modulation data. We have shown that an analysis of the main features of these susy configurations is within the reach of present or planned experimental set–ups. In particular, we have obtained the following results:

- MSSM: The sizeable neutralino–nucleon elastic cross–sections, implied by the annual modulation data, entail a rather stringent upper bound for m_h in terms of $\tan\beta$. In particular, this property implies that no susy configuration would be allowed for $\tan\beta \lesssim 2.5$. Another property, discussed in Ref. [5], is that the annual modulation data and the $b \to s + \gamma$ constraint complement each other in providing a correlation between $\tan\beta$ and the mass of the lightest top–squark.
- SUGRA: In the universal SUGRA model the constraints imposed by the DAMA/NaI data imply for the h–Higgs boson mass, the neutralino mass and the lightest top–squark mass, the following ranges: $m_h \lesssim 115$ GeV, 50 GeV $\lesssim m_\chi \lesssim 100$ GeV and 200 GeV $\lesssim m_{\tilde{t}_1} \lesssim 700$ GeV, respectively.

In universal SUGRA $\tan\beta$ is constrained to be large, $\tan\beta \gtrsim 42$, whereas, with departure from universality in the scalar masses, the range for $\tan\beta$ widens to $10 \lesssim \tan\beta \lesssim 50$.

Many of the above configurations will be explored by LEP2, and almost all of them are under reach of the future planned high–energy accelerators, namely the upgrade of the Tevatron and LHC.

The same configurations can also be probed by indirect dark matter searches. We have shown [7] that a sizeable fraction of the susy neutralino configurations singled out by the DAMA/NaI data may provide signals detectable by measurement of cosmic–ray antiprotons and detection of neutrino fluxes from Earth and Sun.

For the case of cosmic antiprotons, it has been shown [7,17] that present data are well fitted by total spectra which include a $\bar{p}$ contribution from neutralino–pair annihilation, with neutralino configurations which are relevant for annual modulation in direct detection. These data can also be used to reduce the total sample of the susy configurations under study, and to narrow the range of the local density, by disfavoring its largest values. Investigation by measurements of cosmic $\bar{p}$'s looks very promising in view of the collections and analyses of more statistically significant sets of data in the low–energy regime which are currently under way and which may soon provide further relevant information, like, for instance, in the case of BESS and AMS detectors.

Measurements of neutrino fluxes from Earth and Sun, due to capture and annihilation of neutralinos inside these celestial bodies, have been proved to be sensitive to neutralino configurations singled out by the annual modulation data. However, an appropriate interpretation of these measurements preliminarily requires some clarification of the oscillation neutrino properties, especially in the light of the recent Kamiokande result [18].

Finally, we conclude with a few comments. A solid confirmation of the annual modulation effect, as singled out by the DAMA/NaI Collaboration, necessarily requires further accumulation of data with very stable set–ups over a few years, a project which is currently undertaken by the DAMA/NaI Collaboration. For the status of the experimental activity in WIMP direct search with other detectors, see the contributions of the various experimental Collaborations to these Proceedings.

It is really worth noticing that the detection of the effect of annual modulation, if confirmed by further experimental evidence, would turn out to be a major breakthrough in establishing the existence of particle dark matter in the Universe, and this would henceforth be a major breakthrough for astrophysics, cosmology and particle physics as well.

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